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I HEREBY RECOMMEND THIS PLAN B PAPER BE ACCEPTED AS FULFILLING THIS PART OF THE DEGREE, M.S. IN ED.

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INTRODUCTION

From the time fire was first used by man, energy has been the prominent factor in the civilization of mankind. Energy has been used to protect man and to help nourish him since the beginning of his existence. He has developed ingenious methods of using, transferring, and changing the available energy so that he might better his environment. Today, man is still striving to find new and better methods of extracting energy from available sources.

Man's continued existence on this planet can best be shown if one considers the increased rate of energy consumption, the rate of increase of the individuals populating this planet, and what may be needed in the future if the human race is to be maintained.

Professor Harrison Brown and his associates made several studies on energy consumption and arrived at some very startling figures. Brown assumed that in the very near future the world's population would reach a figure of 7×10^9. His values of energy consumption are based on this number. The total yearly energy consumption would be 1.9×10^{18} Btu or the equivalent of 70×10^9 tons of coal per year. At this ultimate rate, the present fossil fuel reserve of approximately 2.4×10^{12} tons would be exhausted in less than 35 years.[1]

With today's rapidly increasing population and dwindling supply of natural resources, scientists are working frantically to develop some method by which the large demand for energy in the future can be met. Among the possible solutions to this problem, sunlight, primary nuclear sources, and energy converters seem the most feasible. This article will be concerned with but one of these solutions, primary nuclear sources, under which there are two main categories, fusion and fission.

FISSION

The Italian physicist Fermi's discovery of nuclear reactions by bombarding uranium with neutrons, and the extension of this work by the German chemists Hahn and Strassman, led, in 1939, to the process of nuclear fission. During the course of their work they developed the theory involved in the fission of ${}_{92}U^{235}$. They showed that the following was true:

$${}_{92}U^{235} + {}_{0}n^{1} \longrightarrow {}_{36}Kr^{92} + {}_{56}Ba^{141} + 3{}_{0}n^{1} + \text{energy}$$

where the subscript represents the atomic number and the superscript the atomic weight of the substance based on the element oxygen as being exactly 16. That is, when an atom of ${}_{92}U^{235}$ is struck by a neutron of relatively high kinetic energy, since there is no Coulomb force being exerted, the neutron may penetrate the nucleus of the uranium. Its presence in the nucleus of the atom may cause the nucleus to become very unstable and undergo cleavage or splitting into two isotopes of lighter elements with a subsequent release of neutrons and a large amount of energy. The energy released can be accounted for by adding the total mass represented by product neutrons and the mass numbers of the two radioactive product isotopes, and observing that this sum is less than the sum of the masses of the reacting materials. A certain amount of mass has thus been converted in the process of cleavage. This mass has been converted to energy according to Einstein's equation $E = mc^2$. Calculations show that the energy release per $_{92}U^{235}$ atom undergoing fission is of the order of 200 Mev.

The fission of a relatively small number of $_{92}U^{235}$ atoms is of little value since the energy liberated would be small in relation to the energy put into the system in getting the neutrons to a high enough kinetic energy to produce fission. In order to take advantage of the fission process a method must be devised by which a large number of atoms will undergo reaction. The ideal condition being a reaction such that one fission may induce other fissions or produce a chain reaction.

These chain reactions break down into two main types, controlled and uncontrolled. The uncontrolled type has been achieved in the atomic bomb explosions. Nuclear explosions are produced by placing a predetermined amount, critical mass, of $_{92}U^{235}$ or $_{94}Pu^{239}$, such that, the neutrons liberated by the fission of one atom will produce fissions in other atoms, etc.

This implies that there will be a tremendous release of energy.

The second type of chain reaction is the controlled type and is achieved in nuclear reactors which are in action at a large number of sites in the United States. These nuclear reactors, or atomic piles, the first of which was built at Oak Ridge, Tennessee in 1943, use a variety of materials, but in general they all apply the same procedure for fission. These reactors contain some type of moderator to slow the neutrons liberated and a series of control rods to absorb some of the liberated neutrons. This regulation of the number of free neutrons helps to slow the chain reaction and therefore it can be controlled and the liberated energy used.

There are two factors which tend to limit the use of fissionable materials as an energy source: First there is a large amount of radioactive waste which must be eliminated and secondly the available amount of fissionable material, according to a recent Atomic Energy Commission report released by Harvey A. Wagner of the Detroit Edision Company, is roughly 23 times that of fossil fuel, and therefore would represent only a few decades of energy in the world of a century from now.[1a] These two obstacles will prevent controlled fission from supplying the energy needed by the civilized world of the future, and a different method must be found to supply this necessary energy. The thing which seems promising will be considered next; the extraction of energy by controlled fusion.

FUSION

The heavier atoms are not the only ones which can release energy. If two atoms are combined into one, there may be a subsequent release of energy. This can be visualized if one considers two deuterium nuclei combining to form $_2He^4$; there is a mass difference of .025607 mass units. This mass is converted to energy. In all fusion reactions the objective is to get nuclei to combine. Since fusion is concerned with the nuclei of atoms all of which have a positive charge, some difficulty in overcoming the Coulomb barrier which will exist between them may result. As a result of the Coulomb barrier, which is directly proportional to the charge, elements whose nuclei have as small a net charge as possible must be used. As an example: Two carbon nuclei, of atomic charge +6 would require collision energies of the order of 36 times that necessary to cause deuterium nuclei of atomic charge +1 to fuse.[2]

Nuclear fusion is not a new phenomenon. In the early 1930's physicists working with particle accelerators found that by accelerating protons and other light nuclei to high enough energies they could cause the particles to break through the Coulomb barrier and fuse with the nuclei of atoms, resulting in a net release of energy. Specifically, in 1932 two English scientists, Cockcroft and Walton, bombarded lithium with protons and found the following equation to be true:

$_3Li^7 + {}_1H^1 \rightarrow {}_2He^4 + {}_2He^4$ + energy. The difficulty in this type of reaction is that even though there is a great deal of energy liberated, much more energy must be put into the system to attain a few fusion reactions. If there is no net gain in energy over the reaction then the process is not feasible as a power source.

If one is concerned with a net release of energy in a fusion reaction then there must be a new scheme developed to acquire the energy. The most promising method seems to be the plan by which the nuclei are raised to a very high temperature, of the order of several million degrees, and placed in some type of container. Because of this type of confinement a particle will move about inside the container with random motion and will eventually collide with another nucleus, and fusion may result. This allows a given number of nuclei, over a period of time, to fuse.

The reactions which will be considered are listed below:

$$
\begin{aligned}
{}_1H^2 + {}_1H^2 &\longrightarrow {}_2He^3 + n + 3.25 \text{ Mev} \\
{}_1H^2 + {}_1H^2 &\longrightarrow {}_1H^3 + p + 4 \text{ Mev} \\
{}_1H^3 + {}_1H^2 &\longrightarrow {}_2He^4 + n + 17.6 \text{ Mev} \\
{}_2He^3 + {}_1H^2 &\longrightarrow {}_2He^4 + p + 18.3 \text{ Mev} \\
{}_3Li^6 + {}_1H^2 &\longrightarrow 2\ {}_2He^4 + 22.4 \text{ Mev} \\
{}_3Li^7 + p &\longrightarrow 2\ {}_2He^4 + 17.3 \text{ Mev}
\end{aligned}
$$

If these reactants are placed in some type of container and heated to several million degrees, one has what is commonly referred to as a plasma.

PLASMA: DESCRIPTION AND BEHAVIOR

If one considers a liter of deuterium gas at standard temperature and pressure, confined to a certain volume, the average kinetic energy of a molecule is about one 25th of an electron volt. The average energy per particle is $\frac{3}{2}$ kT, where k = 1.38×10^{-23} joule/^{o}K and 1 (ev) = 1.602×10^{-19} joule.

If the gas is now heated to 5,000 ^{o}C the covalent bonds holding the atoms together will break causing only atoms to exist, because of the violent thermal agitation. The pressure will be about 40 atmospheres and the average velocity of the atoms is about 40,000 miles per hour. This temperature is still much less than that necessary for a fusion reaction. To get energies sufficient for the desired results, temperatures of the order of 100 million degrees must be acquired. At this temperature the deuterium atoms have broken down into deuterons and electrons. That is, the thermal agitation is such that the binding energy of the atom is not sufficient to hold the atom together, and therefore the electrons are stripped from the nucleus. At this temperature the pressure will be 1.5 million atmospheres; the electrons will be traveling at 90,000 miles per second, and the deuterons at 1,500 miles per second.[3]

One can see several significant factors in this set of values. To contain these particles will require starting with particles at a very low pressure, since the pressure becomes so great at high temperatures, and a container must be developed which will not be vaporized by the collision of the high energy particles with the atoms of the container. The most promising type of container is one which utilizes a magnetic field as the confining element. This will be discussed at a later point.

When one considers a pair of nuclei approaching each other, there are two possible results. The nuclei may scatter, due to their mutual repulsion, or they may collide and fuse together. Since the concern is with the latter case, the probability of the event occurring should be calculated. The total reaction rate per unit volume is determined by:

$$R_{12} = n_1 n_2 \; (\sigma \; v_{12})_{Av} \qquad (1)$$ [4]

reactions/cm^3/sec, where n_1 is the particle density of atoms of type 1, n_2 is the density of type 2, σ is the mutual reaction cross section determined by the relative velocities of the ions, and v_{12} is the relative velocity of the ions which must be averaged over a Maxwellian distribution. The term $(\sigma \; v_{12})_{Av}$ can be obtained by the equation:[2]

$$(\sigma \; v_{DD}) = 2.6 \times 10^{-14} \, (T^{-\frac{2}{3}}) \, e^{-18.76 \, T^{-\frac{1}{3}}} \qquad (2)$$

where v_{DD} corresponds to v_{12} as defined above, and in this case represents the relative velocities of two deuterium ions.

At very high temperatures the atoms are completely dissociated into ions, and these ions move about with random velocities. The fusion reaction cross section is observed to be a function of the temperature or kinetic energy as shown by figure 1.